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120MM PRESTRESSED CARBON FIBER/THERMOPLASTIC OVERWRAPPED GUN TUBES

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Abstract

The emphasis on lightweight large caliber weapons systems has placed the focus on the use of advanced composite materials. Using composite materials not only directly removes weight from the gun tube but, by better balancing the tube, allows the use of smaller drive systems, thus further enhancing the system weight loss. Additionally the use of high stiffness composites helps with pointing accuracy and to alleviate the dynamic strain phenomenon encountered with high velocity projectiles.

Traditionally there were two issues with composite jackets: the coefficient of thermal expansion mismatch between the steel substrate and the composite jacket causing a gap, and the lack of favorable prestress in the jacket. Dealing with these issues greatly complicated the manufacturing process to the point where mass-producing the barrels would have been problematic at best. By using a thermoplastic resin, a cure on the fly process and winding under tension the manufacturability of the barrels has been greatly improved, the gap has been eliminated, and a favorable prestress has been achieved.

Four 120mm barrels have been manufactured using this process with IM7 fibers in a PEEK matrix and successfully test fired. The first barrel was not prestressed and was reported on previously. This paper will focus on the other three barrels. The design, manufacturing, and test firing of these barrels will be covered.

Contents

Introduction

Previous composite wrapped gun tube efforts have been undertaken by Benét Laboratories during the late 1980's and early 1990's. These efforts led to the fabrication and test of several 105mm and 120mm gun tubes. An outcome of this work was the need to prevent or eliminate the formation of a gap, on the order of 0.1 mm (0.004 in), between the composite overwrap and gun steel liner during the composite curing process. The gap formed due to the coefficient of thermal expansion (CTE) mismatch between steel and composite. This gap effectively prevented or reduced the load carrying capability of the composite. To overcome the problem, the gun tube was autofrettaged (method of achieving compressive residual stresses at the bore by plastic deformation) after the application of the composite. The autofrettage effectively closed the gap, and also imparted some favorable residual stresses to the gun tube structure. There were, however, two problems with this approach; first, the thermal soak treatment used to stabilize the residual stresses in the tube after autofrettage could not be conducted. The thermal soak is done at temperatures of 343 to 371 °C (650 to 700 oF) which is well above the maximum use temperature of the composite. The second problem was that the tube could not be chrome plated since the process requires the tube to be immersed in chromic acid, which would destroy the composite and contaminate the plating bath. The third problem is the creation of extremely high radial stresses at the steel / composite overwrap which may be higher than firing stresses [1]

One approach to solving these problems was the 105mm Multi-Role Armament and Ammunition System (MRAAS) Swing Chamber Launcher [2]. In this case the CTE mismatch was handled by tailoring the lay-up. A combination of fiberglass and graphite was used with the ply angles being adjusted such that the lay-up's CTE matched that of the steel. This resulted in no gap forming between the composite and the steel but the performance of the composite was not optimum.

The composites used on these efforts were all thermoset materials; therefore the curing process took place after composite wrapping. For the current Advanced Technology Demonstration (ATD) effort, thermoplastic composites will be used. The advantage of thermoplastics is that they do not need a cure cycle but can rather be melted and recrystalized / consolidated immediately after being placed on the gun tube. This results in a "cure in place" type fabrication technique. Heating of the composite is localized, minimizing heat input to the composite and gun tube. This process mitigates thermal expansion effects and effectively eliminates the gap problem. The composite can therefore be placed onto the gun tube after the autofrettage thermal soak and chrome plate application.

One of the challenges of the composite wrapped gun tube will be handling the dynamic loading environment of a gun tube. Firing data of gun tube strain have shown that the measured strains are typically higher than expected from static ballistic pressure alone. This increase in tube strain is attributed to both the loading condition, which is effectively a square wave, as well as high speed dynamic loading of the gun tube during projectile passage. In most cases, this strain is typically 8-10% above the statically predicted (open ended cylinder, Lame equations) values. In situations where thin walled gun tubes and high velocity projectiles are used, the strains can be significantly higher, on the order of 300-400%. This phenomenon is known as gun tube dynamic strain and has been an area of study for many years by Benét Laboratories [3, 4, 5].

In the development of the Light Weight 120mm (LW120) cannon, this phenomenon will be of special interest since the LW120 will have a thinner tube wall than the current 120mm M256 cannon and thus it will be more prevalent.

The 120mm Line of Sight / Beyond Line of Sight (LOS/BLOS) ATD is tasked to design, develop & demonstrate new armament & ammunition technologies for use in the Army's Future Combat System (FCS). The specific role the ATD plays is to support the development of the main armament for the Mounted Combat System (MCS), which will be equipped with a 120mm main armament and will provide Line of Sight and Beyond Line of Sight firing capabilities.

One of the tasks assigned to the 120mm LOS/BLOS Gun Assembly Team was to provide a light weight 120mm gun assembly for the MCS vehicle. The focus of this report is the use of an organic composite overwrap to lighten the weight and reduce the imbalance of the gun tube. The ATD was tasked with delivering six 120mm gun tuibes, four of which were composite overwrapped. The first tube, Serial No. ATD-1, was the first large caliber gun tube to be wrapped with thermoplastics and was reported on previously [6]. This report will focus on the other three composite wrapped tubes. Their serial numbers are: ATD-3, ATD-5 and ATD-6. These tubes use the same materials as ATD-1 but they have very different lay-ups and were the first gun tubes to be wrapped under tension.

Design and Analysis

Initially a lightweight all steel 120mm gun tube was designed using traditional methods. The steel design had a weight of 889 kg and was 5460 mm in length. The goal of the composite design was to match or exceed the frequency of the first bending mode of the steel design as well as match the residual hoop stress distribution through the gun tube wall, while saving weight.

Thermoplastic composites were used instead of thermosets in order to take advantage of the "cure in place" fabrication technique. Additionally applying the composite under tension helped to build in a favorable prestress in the composite jacket. Besides this manufacturing consideration, the composite overwind had to be able to withstand the significant forces and heat fluctuations associated with firing the weapon.

IM7 fiber with a polyetheretherketone (PEEK) matrix was the material selected for this project for several reasons. The first is the superior strength (2.07 GPa (300 ksi) in the fiber direction), modulus (138 GPa (20 msi) in the fiber direction) and toughness of the composite when compared to the majority of thermoset and other thermoplastic materials. The second reason for the selection of this material was its high melt point (653 °F / 345 °C). The final reason for the selection of this material was its excellent chemical resistance; in particular, its resistance to petrochemical fluids that would be encountered in the day to day operation of a large machine. The cost of thermoplastics, while in general higher than thermoset counterparts (~20%), was offset by the fact that there would be no autoclave post cure required. With a shape as complex and large as this, bagging and autoclaving add significant expense (up to 20%) to thermoset processing, plus the capital investment in a large autoclave (approx $300,000 for one large enough to process this gun tube), making thermoplastics a competitive alternative.

With the fiber/matrix selected the lay-up itself had to be designed. The two main design goals for the gun tube were to match or exceed the frequency of the first bending mode of the all steel design as well as match the residual hoop stress distribution through the gun tube wall. The tubes natural frequency (especially the first bending mode) affects the gun aiming and stabilization system. Maintaining the same natural frequency as the current gun tube minimizes changes to these systems. In addition, if the tube natural frequency gets too low, it may approach the natural frequency of the riding loads of the vehicle. Excitation of the gun tubes natural frequency may then occur leading to a condition in which stabilization of the gun tube becomes impossible.

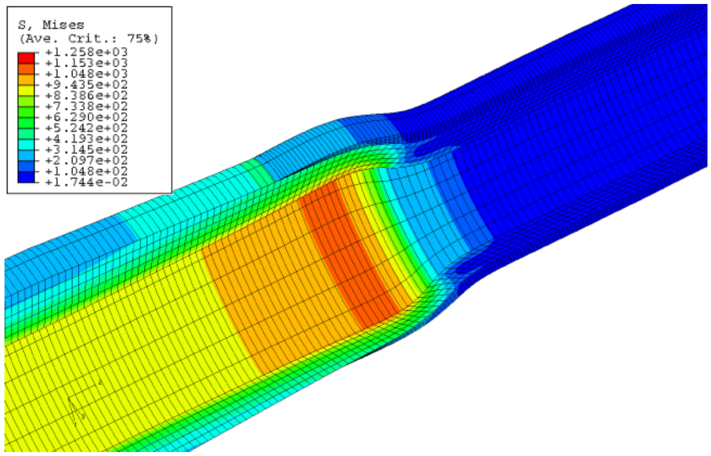

Figure 1: Dynamic FEA analysis of a steel tube with a composite jacket – Mises stress, 100x magnification

Large caliber gun tubes often use autofrettage to impart favorable residual stresses into the gun tube structure. Since we were replacing some of the steel with composites, it was vital that the composite provide the same residual stress distribution as the original steel. To accomplish this, the residual stress distribution through the tube wall, including autofrettage and the composite wrap, was modeled using the WIND Composite Cylinder Design Software Tool developed by the University of Delaware Center for Composite Materials.

With the WIND software the geometry of the steel tube and the composite lay-up are entered. The code then generates the strains and stresses in each ply in the radial, hoop, and axial directions under an applied pressure loading. The autofrettage parameters, winding tension, ply start, ply stop, material and orientation, can be changed for each ply. Using this code, a candidate lay-up was designed and then sent to Abaqus for a dynamic finite element analysis (FEA).

Previous work at Benét Labs [7] was employed to properly model the dynamic effects of a pressure wave moving down a gun tube and to ensure the correct high frequency data was captured. An axisymmetric FEA model was created using 8-node biquadratic axisymmetric quadrilateral reduced integration elements (CAX8R).

There are three ways that the composite jacket can be joined to the steel substrate. The first is to use tie constraints to simulate perfect bonding. The second option is to allow sliding but no separation between the parts. The third is to allow both sliding and separation. In the previous

work on ATD-1 [6] it was determined that the differences between these three approaches were <<5%. This indicated frictional and bending forces were low enough such that the composite and steel interface never separated or slipped relative to each other, so tie constraints were used for the FEA models.

Smeared orthotropic properties were used for the composite. This decision was also based on work from ATD-1 [6] where results with ply by ply and grouped ply properties were found to be similar (<<5% difference) to ones using smeared properties.

Static, normal mode and dynamic analyses were all performed. For the dynamic analysis, a pressure load was moved down the bore of the tube to simulate a projectile. A graphical result of this analysis can be seen in Figure 1.

These analyses were repeated until a lay-up was arrived at that met or exceeded all of the metrics. The final layup consisted of 72 plies of IM7/PEEK with a mixture of hoop and axial plies. The hoop plies were wound under tension to match the residual stress distribution of the original all steel design. A cross ply layer of S2/PEEK was added to the outside to protect the carbon fiber layers. This lay-up resulted in 113.4 kg (250 lbs) of steel being removed and 20.4 kg (45 lbs) of composite being added for a net weight savings of 93 kg (205 lbs).

Manufacture

The steel portion of the gun barrel was manufactured according to the normal process, except that an area was undercut for the composite.

The composite was applied utilizing a robotic fiber placement process developed by Automated Dynamics Corporation (ADC) of Schenectady, NY to precisely place and consolidate strips of thermoplastic prepreg tape. The process uses a hot gas torch (HGT) to melt the prepreg and then consolidates it with a pressure roller as shown in Figure 2. Throughout the process the tape is held under tension and upon cooling this tension is locked in; inducing a residual stress into the part.

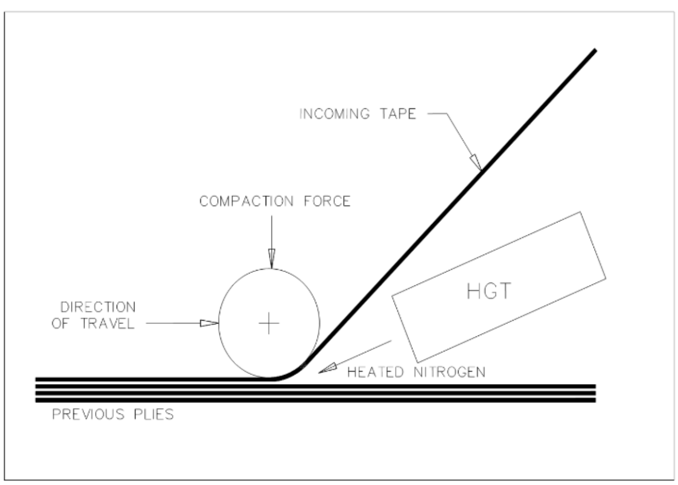

Figure 2: ADC In-situ Consolidation Process

There were three major issues that needed to be overcome in order to fabricate the overwind:

- Tightness of fit between overwrap and barrel
- Galvanic corrosion between overwrap and barrel
- Maintaining the desired outside diameter (OD)

Winding under tension helps to ensure a tight fit between the overwrap and barrel but beyond this it was decided to cool the barrel, thus causing it to shrink during processing. Upon returning to room temperature the barrel attempts to grow in size but is constrained by the composite. In this way we are using the CTE mismatch to help form a tighter fit between the steel and composite instead of a gap, as was the case in older thermoset overwrapped gun tubes. This cooling process was found to induce level of residual stress equivalent to approximately 133 N (30 lbs) of winding tension.

Additionally the cooling helps to remove the heat generated from the fiber placement process. Without cooling the barrel temperature would have quickly heated to between 60 and 65 °C (140 to 150 °F). The exact temperature the barrel was cooled to cannot be released but it was within the operational temperature of the gun system so it will not adversely affect the mechanical properties of the steel. The temperature was monitored at the coolant inlet, the breech, and muzzle. These three values were then used to control the amount of coolant introduced into the tube to maintain the desired substrate temperature.

If carbon fiber is brought into direct contact with steel, galvanic corrosion would take place. To avoid this, two layers of S2 fiberglass / PEEK were placed between the steel and the carbon fiber. Since the matrix is the same (PEEK), the bond between the graphite composite and the insulating layer is excellent. The CTE of this layer is higher than the carbon layer but still lower than the steel so it will not adversely effects the tightness of the steel/composite fit. This layer was accounted for in the FEA model.

Due to some standard variation in raw material thickness (specification for the material allows a +/-0.0127 mm variation in tape thickness), close attention was paid to the OD during fabrication. Modifications to ply lengths and locations were made to maintain the desired final OD.

Figure 3 shows an axial ply being applied to the gun barrel. The white area is frost that develops on the part due to the chilling of the barrel. The hot gas torch vaporizes this as it applies the tape, so that none of the moisture finds it way into the part.

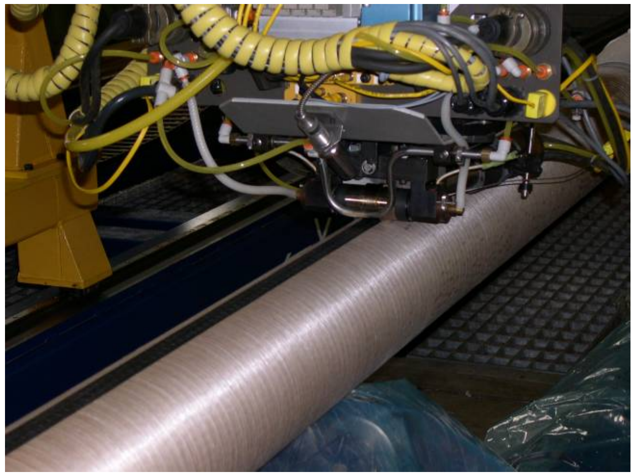

Figure 3: An axial ply being applied to the gun barrel

This same basic process was used for all three tubes but there were some improvements made over the course of wrapping the three tubes. ATD-3 was fabricated by Automated Dynamics while they were fabricating Benét's new fiber placement machine. They used 25 mm (1 in) wide tape during fabrication so the outer cross-ply layer was wrapped at +/- 75 degrees. Also the automated cooling system was still in development so the cooling was performed manually. After wrapping it was found that the ends of the cross-ply layer were prone to peeling. To solve this, the ends were coated in a thin layer of epoxy.

ATD-5 and ATD-6 were wrapped in house at Benét on the new fiber placement workcell designed and fabricated by Automated Dynamics. In this new system the tension and cooling were directly controlled by the machine with limited operator intervention. 12.5 mm (0.5 in) tape was used for wrapping these tubes so the cross-ply was done at +/- 45 degrees. To prevent the cross-ply peeling issue a 203 mm (8 in) +90 / -90 band was added to each end of the lay-up.

Non- Destructive Evaluation

Besides checking tube straightness modal impact, pressure, and acoustic emission (AE) testing were all performed to assess the state of the composite overwrap. Ultrasonic inspection was planned if any of the tests uncovered possible areas of damage.

Modal impact testing was performed prior to applying the composite and after applying the composite to determine effect of the overwind on tube stiffness. Modal testing was also planned for after firing for all three tubes to look for any detrimental effects of the test firing, however other higher priority testing precluded this form being done on all tubes except ATD-3. In all cases the tube was hung from springs to simulate free-free boundary conditions. This setup can be seen in Figure 4.

Figure 4: ATD-6 Modal Testing Setup

Accelerometers were placed at the muzzle and every foot (304.8 mm) down the length of the composite. For ATD-3 and ATD-5, the tube was impacted 219 mm (8.625 in) from the muzzle with a modal impulse hammer and the response of the accelerometers was recorded. After this, all but the muzzle accelerometer were removed and the tube was then impacted at each previous accelerometer location. For ATD-6 the modal hammer was used for the pre-wrap test but for the post-wrap test a 222 N (50 lb_f) modal shaker was used to apply the impulse.

The results of this testing for the first three modes can be seen in Table 1. The composite wrap slightly increased the stiffness of the gun. These results were compared to the FEA analysis and were found to be in good agreement. Not only did this result help to validate the FEA models but also ensured that energy was being transferred from the composite to the steel and vice versa.

Table 1: Modal Testing Results

		Mode (Hz)		
		First	Second	Third
ATD 3	Pre Wrap	26.50	81.00	174.00
	Post Wrap	28.75	85.25	178.75
	Post Firing	28.50	85.25	178.75
ATD 5	Pre Wrap	26.00	892.25	169.75
	Post Wrap	28.25	83.50	173.75
ATD 6	Pre Wrap	22.50	77.00	165.00
	Post Wrap	26.75	80.81	168.80

The pressure and AE tests were conducted at the same time as they both required pressurizing the gun tube. The pressure test helps to ensure that there is no gap between the steel and the overwrap. If a gap exists then there would be a delay in the composite picking up the pressure load applied to the bore. For the AE test the tube is pressurized twice. The first time there will be some fiber and matrix cracking as any defects need to work themselves out. The second loading should be quiet. If the second loading produces any noise events they could be an indication of damage and need to be investigated.

Standard rosette strain gages were placed at two axial locations along the length of the composite. At each location a gage was placed at the 12, 3, 6 and 9 O'clock positions. The gauges were oriented to record both hoop and axial strain. These same gauges were later used in the firing test. The tube was pressure tested to a peak pressure of 68.9 MPa (10 ksi). The strain readings were recorded every 6.89 MPa (1000 psi) up to peak pressure.

Eight Physical Acoustics R-151 acoustic emission sensors were set up in an F-array so that the location of any suspected damage could be located. The mandrel used to pressurize the tube was only 1828.8 mm (72”) in length so the pressure/AE test had to be conducted twice to cover the entire length of the composite. The strain data collected, during the pressure test, was in good agreement with predictions and within 3% of the FEA analysis.

Firing Results

The guns were taken to Aberdeen Proving Ground (APG) at different times from 2004 through 2007. The guns were fired in direct and indirect fire modes with strain data being taken

for the direct fire shots. During these shots a series of two round types were fired at both ambient and hot conditions. Figure 5 is a photo of a direct fire shot.

Figure 5: Test firing at APG

The test instrumentation used was standard rosette strain gauges. Gauges were placed at two axial locations along the composite area of the tube. At each axial location a gage was placed at the 12, 3, 6 and 9 O'clock positions. Measurements were recorded for the axial and circumferential (hoop) strain. Capturing strain data in this environment can be very challenging so for some firings dozens of rounds were recorded whereas for others only a few rounds of reliable data were captured.

Table 2 gives both the theoretical and experimental hoop strains for the round types fired. Looking at the table it can be seen that there is good qualitative and quantitative agreement between theoretical and measured strain levels.

Table 2: Experimental and Theoretical Hoop Strains

	ATD-3		ATD-5				ATD-6	
Round Type	#1	#2	#1		#2		#2	
		Hot	Ambient	Hot	Ambient	Hot	Ambient	Hot
# of Rounds			8	3	54	3		
Location 1 Experimental	Mean 1755 Std Dev 33	Mean 1766 Std Dev 86	Mean 1693 Std Dev 109	Mean 1931 Std Dev 92	Mean 1724 Std Dev 95	Mean 1758 Std Dev 99	Mean 1819 Std Dev 248	Mean 1930 Std Dev 288
Location 1 Theoretical	1527	1719	1665	1709	1721	1796	1721	1719
Location 2 Experimental	Mean 2160 Std Dev 145	Mean 1933 Std Dev 289	Mean 1863 Std Dev 130	Mean 2258 Std Dev 180	Mean 1690 Std Dev 127	Mean 1771 Std Dev 101	Mean 1792 Std Dev 549	Mean 1806 Std Dev 528
Location 2 Theoretical	1575	1922	1786	1989	1766	1926	1796	1922

For ATD-3, the response for the round type 1 was higher than expected but this is believed to be due to higher than expected pressures generated by the round. The results for round type 2 (the worst case round) were excellent with test results at both locations within 3% of theoretical.

For ATD-5, the response for the hot rounds was higher than expected but this is believed to be due to higher than expected pressures generated by the round. The results for round type 2 ambient were excellent with test results at location 1 being within 1% of theoretical and location 2 being within 5%.

The results for ATD-6 are not as good as the other two. There were many problems with data collection during the test firing so the results are not as good as the other two. The large standard deviations show that there was a large amount of scatter in the data. Still with the exception of location 1, hot the means were within 6% of theoretical.

For ATD-3, Figure 6 and Figure 7 show the experimental and theoretical strains vs. time at axial location 1 for both round types. Looking at the figures it can be seen again that there is very good agreement for round type 2. For round type 1, the response is higher than expected.

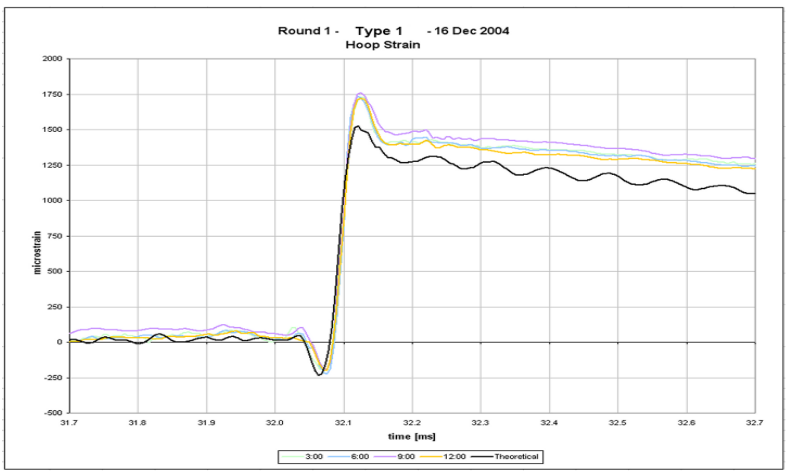

Figure 6: ATD-3 Location 1, Type 1, Strain vs. Time

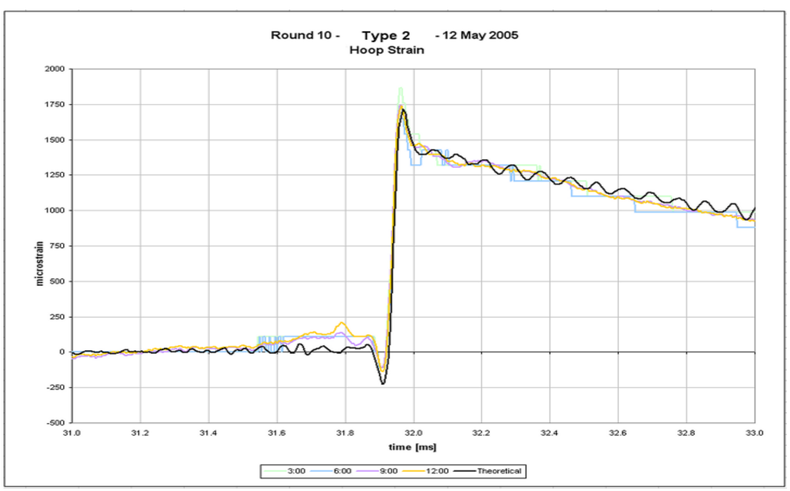

Figure 7: ATD-3 Location 1, Type 2, Strain vs. Time

As mentioned earlier this is due to the higher than expected pressures seen in this round.

For ATD-5, Figure 8 and Figure 9 show the experimental and theoretical strains vs. time at both axial locations for both round type 1 ambient. Looking at the figures it can be seen again that there is very good agreement between theoretical and experimental results at location 1. At location 2, it can be seen that the experimental results did not damp out as quickly as predicted but the overall agreement is still very good.

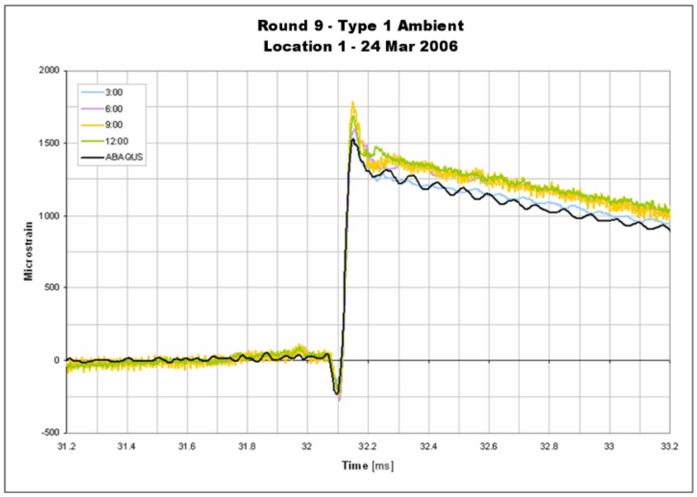

Figure 8: ATD-5 Location 1, Type 1, Strain vs. Time

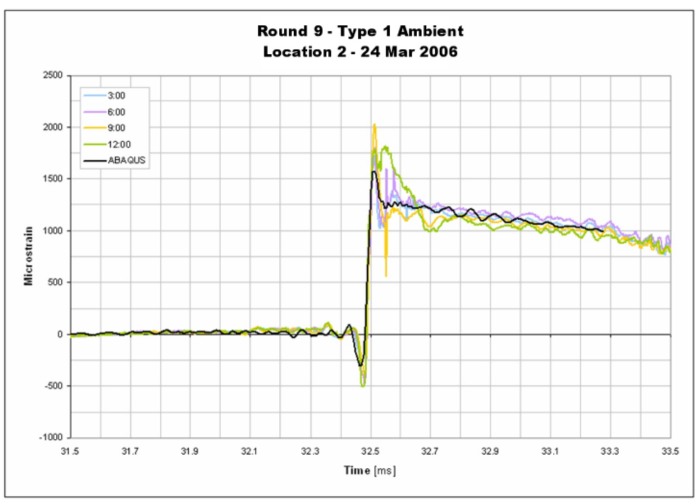

Figure 9: ATD-5 Location 2, Type 1, Strain vs. Time

For ATD-6, Figure 10 and Figure 11 show the experimental and theoretical strains vs. time at both axial locations for both round type 2 hot. Location 1 shows very good agreement between theoretical and experimental. At location 2 however there were problems with data collection and the results are nor as good. The trend is still the same but the experimental response was less than predicted.

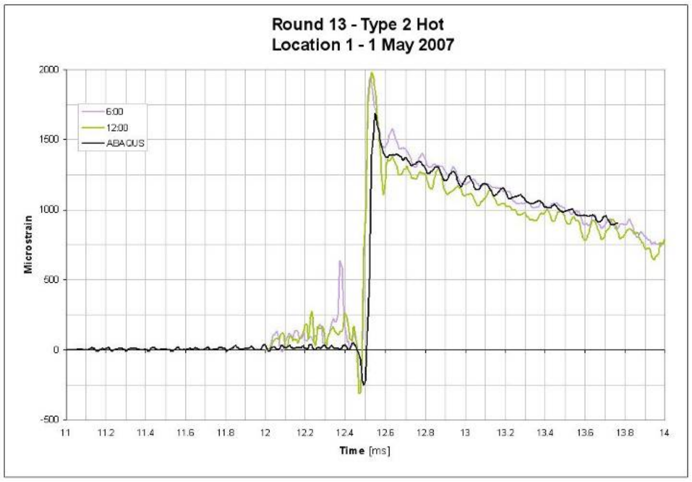

Figure 10: ATD-6 Location 1, Type 2, Strain vs. Time

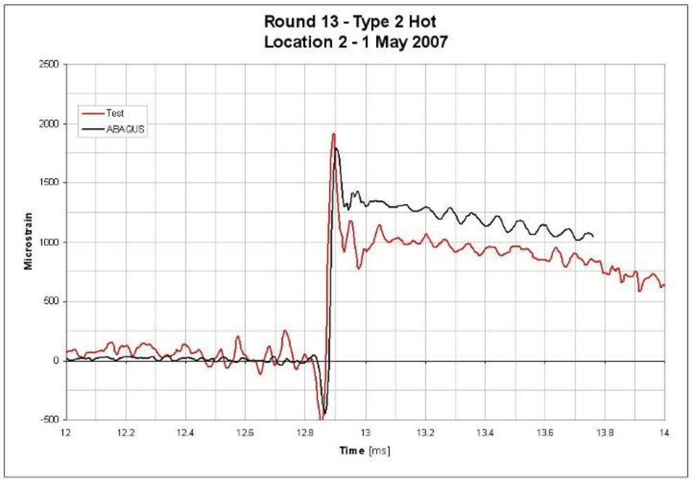

Figure 11: ATD-6 Location 2, Type 2, Strain vs. Time

CONCLUSION

Three lightweight composite wrapped 120mm gun tubes were successfully designed, manufactured, and test fired. A thermoplastic matrix was used, allowing for cure in place fabrication. This avoided the manufacturing complications due to coefficient of thermal expansion mismatch encountered in previous attempts at composite wrapped gun tubes. The prepreg was applied under tension resulting in a favorable prestress in the composite jacket. The design resulted in a gun tube that was 205 lbs lighter than its all steel counterpart while maintaining the same first bending mode and cross sectional profile.

Finite element models were used to help predict the response of the gun tube to firing loads. These models were validated through non-destructive testing and later shown to be in good agreement with the firing results. The composite jacket survived the firing with no apparent damage.

Overall, this effort was very successful and the data collected will be very useful in the design of future composite wrapped gun tubes. In fact the basic design has been selected as the baseline design for the main armament for the Future Combat Systems-Mounted Combat Systems vehicle. Currently the design is undergoing more detailed testing / optimization under the System Design and Development portion of that program.

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